

Upper Ocean Response to Tropical Cyclones

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LONG-TERM GOAL AND OBJECTIVES

The long-term scientific goal of the research is to understand key physical processes governing the upper ocean's thermal and momentum response to the passage of tropical cyclones over near-inertial time scales. The investigation examines the evolving 3-dimensional upper ocean structure excited by the passage of tropical cyclones using a blend of *in situ* and satellite-based measurements, theoretical treatments, and numerical simulations. Specific objectives of the study are:

- i) To examine the importance of the density structure and geostrophic currents on both the upper ocean response and the forced near-inertial motions including the propagation of energy from the mixed layer into the thermocline;
- ii) To determine the atmospheric forcing structure and its impact upon the upper ocean response; and
- iii) To assess the relative roles of advection and mixing processes on the evolving 3-dimensional ocean mixed layer response.

APPROACH

The approach combines aircraft-based oceanic observations from Gilbert with MMS mooring and survey data to document the steady-state and transient upper ocean current response in the presence of a warm core eddy. These profiler data are blended with the ship-based CTD measurements to resolve the salinity and density differences between the eddy and Gulf common water in the western Gulf of Mexico. Upon removal of this steady-state component, the transient response is isolated using near-inertial models in storm coordinates (Shay *et al.*, 1989). Velocity profiles are WKB-scaled to determine the excess clockwise-rotating energy and multiplied by the vertical group velocity for each wavenumber to determine the downward internal wave flux.

Moored current meter observations and the air-sea interaction buoy data from Emily have been collected, processed and filtered. Surface wind and wave spectral energy densities from the NDBC air-sea interaction buoys are correlated to the strong near-inertial subsurface current response over the shelf and slope. To provide spatial context for these effects, remote-sensing signatures of the TOPEX-derived surface height anomalies (SHA) prior and subsequent to Emily and Opal have been collected for further analyses.

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Mixed layer models of Elsberry *et al.* (1976), Pollard *et al.* (1973) and Deardorff (1983) are used to assess the effects of vertical mixing and horizontal advection on the heat and momentum balance. Sea surface temperatures (SST) and mixed layer depths are combined with atmospheric forcing data including the near-surface fields from ECMWF. Simulations from free-surface primitive equation ocean models are being compared to the observed upper ocean response fields during hurricane Gilbert involving the Princeton Ocean Model and the NRL Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS).

TASKS COMPLETED

Aircraft-based oceanic profiler data from Gilbert have been decomposed into the geostrophic and near-inertial components and have been analyzed to produce gridded fields. These fields along with the gridded temperature, mixed layer depth and density fields have been used to estimate entrainment in diagnostic mixed layer models.

Vertical wavenumber spectra have been compared to the Garrett-Munk (1975) spectral levels and theoretical predictions of internal wave power (Nilsson, 1995). Downward internal wave fluxes have been equated to the near-surface winds to determine the functional relationship between these processes. From the hurricane Emily data set, current and density time series have been filtered to form low-frequency, near-inertial and tidal current components over the shelf and slope off Cape Hatteras. In addition, the surface wave spectral energy densities have been band-pass filtered with a center point at the inertial period (20 h), and have been correlated to the coastal ocean current response.

RESULTS

Shay and Chang (1997) found a difference of 7 cm s^{-1} in the depth-averaged current and 5 cm sea-level oscillations between a one-layer and multi-level models due to the depth-averaged mass divergence terms. Since vertical velocity eigenfunctions indicate that the barotropic mode is at least fifty times larger than the surface baroclinic mode, the barotropic mode displacements explain most of the height variations. The first confirmation of these free-surface undulations has been identified in the hurricane Emily data (Faber *et al.*, 1997). That is, filtered wave spectral energy densities reveal a modulation over inertial periods due to these free-surface oscillations that in turn modulate the significant wave heights and surface winds.

Shay *et al.* (1998a) resolved the background and storm-induced geostrophic currents (relative to 750 m) where the typical current speeds are 10 cm s^{-1} and 20 cm s^{-1} . Within the clockwise-rotating warm core ring, geostrophically balanced currents were about 1 m s^{-1} in the surface layer. Upon removal of the geostrophic components, the near-inertial frequency in the mixed layer was shifted above f by a few percent, and a consistent clockwise rotation of the velocity vector with depth is observed as energy propagated downward into the thermocline. The wind stress curl is the dominant forcing mechanism in exciting these motions.

The WKB-scaled clockwise-rotating vertical wavenumber spectra exceeded the counterclockwise-rotating spectra by an average factor of 3.6 (Shay, 1997). The average downward vertical energy flux of about $2 \text{ ergs cm}^{-2} \text{ s}^{-1}$ followed a *tanh* dependence. Based upon this rate, the estimated near-inertial power on a global basis is a factor of 30 times more than the theoretical prediction. This result suggests that strong forcing events, which are ubiquitous over the world's ocean, excite an energetic internal

wave continuum. By equating the observed surface winds to this energy flux, a nonlinear relationship of the form $\tanh(U_{10}^2)$ compared well to a wave-age dependent drag coefficient of Donelan (1990) for winds between 12 to 20 m s⁻¹.

Using diagnostic mixed layer models with three entrainment closure schemes applied to the Gilbert measurements, Jacob (1997) has shown that the geostrophic advection terms contributed significantly to the thermal balance, underscoring the importance of prestorm oceanic variability. With respect to vertical mixing, shear-induced mixing effect dominated the heat balance in the internal wave wake whereas stress-induced effects were important in the directly-forced region. A similar patterns of entrainment mixing events although the locations of the maxima differed between the three schemes relative to the storm center. Temperature and velocity structural observations from Gilbert have been compared to simulations from the Princeton Ocean Model and COAMPS. The location of the OPBL cooling pattern is similar to the observations and agrees with the magnitude of the temperature response of 3°C.

During the passage of hurricane Opal (95), unexpected deepening occurred upon encountering a warm core eddy where the winds increased from 110 to over 135 mph. Relationships between the TOPEX-derived SHA and the underlying density field are used to monitor the upper layer thickness and heat content (Shay *et al.*, 1998b,c). By differencing pre- and post- imagery, the net heat loss is about 10-12 Kcal cm⁻² relative to the depth of the 26°C isotherm, and is above the threshold heat loss value required to sustain a tropical cyclone. Unfortunately, *in situ* measurements of the velocity and density structure were not acquired thereby precluding any estimates of shear-induced mixing events and horizontal advection which have been found to be important in Gilbert. These results were corroborated from numerical guidance from COAMPS where the surface heat fluxes increased by 40% over the warm core eddy (Hong *et al.*, 1998).

IMPACT AND TRANSITIONS

The impact from this research is: i) utilization of observed oceanic and atmospheric fields from synoptic-scale aircraft-based experiments for initialization into oceanic and coupled models; ii) validation of the models by comparing observations to simulations for the purpose of improving storm-scale parameterizations; and iii) the application of these validated models to the operational Navy and civilian needs.

Satellite-based component demonstrates the utility for monitoring the upper layer's heat content in the vicinity of warm fronts and rings for possible intensity changes of tropical cyclones. The analyses of oceanic and atmospheric observations from tropical cyclones (i.e. Gilbert) have been provided to the research scientists for initialization into the NRL COAMPS, University of Rhode Island and operational centers. A key aspect here is to validate simulated fields with observations acquired under severe conditions to improve model parameterizations (i.e. mixing). Satellite-based data products from TOPEX and AVHRR for upper ocean heat content will be transitioned to operational forecast centers.

RELATED PROJECTS

This observationally-based oceanographic research project is relevant to ONR Meteorology research initiatives on Tropical Cyclone Structure and Motion, the NRL COAMPS project, ONR sponsored coupled model efforts at the University of Rhode Island, NOAA's Hurricane Research Division and National Hurricane Center. The oceanic research described herein represents one of the

key air-sea interaction components of the NSF/NOAA United States Weather Research Project program.

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